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ABSTRACT

"Critical fixities," the factors that inhibit change within organizations, are defined and explained in this study. Implications of these phenomena on leap-frog type competition, entry strategy, vertical integration, and timing of investment are derived. The U.S. steel industry and the behavior of firms within this industry are used to illustrate these implications.

Introduction

One of the most significant industrial transformations in the last twenty years in the U.S. is the decline of the smokestack industries such as the automobile and steel industries. The major reason for this decline is the inability of these industries to compete with their international rivals. High labor costs and obsolete equipment have been cited as the main causes in this loss of international competitiveness.

Although high labor costs should have induced firms to replace less efficient equipment with new labor-saving technologies, which have been universally available in these industries, it seems strange, especially at first glance, that steelmakers and automakers suffering from high labor costs have not aggressively adopted these labor-saving innovations. One possible explanation for this seemingly contradictory phenomenon, as argued below, is the existence of "critical fixities", a multidimensional inertia that keeps a firm from responding to change. More specifically, this paper illustrates that, high labor costs notwithstanding, critical fixities could have contributed to the slow adoption of new technologies and thus caused the decline of the steel industry.

This paper is divided into three sections. The first section examines and explains the theoretical foundations of critical fixities; the second section deals with their strategic implications; and the third section discusses the steel industry as an example of the application of critical fixities.

THE NOTION OF CRITICAL FIXITIES

It is generally recognized that if a firm is to succeed in the long run, its strategy should be adapted to environmental changes. For technology intensive industries, a firm's willingness and ability to adapt to technological changes in order to maintain its competitiveness is especially critical to its survival. In industries such as steel because of process technology, the vintage of the manufacturing process affects a firm's competitiveness to a very great extent. Consequently, a key strategic issue is how to adopt process innovation in order to avoid the threats of competitors and profit from increases in efficiency.

A firm adopts a process innovation either as part of the expansion process or at the time of replacement. Since opportunities for expansion in mature industries such as the steel industry, are few because of excess capacity, we will at first search for evidence linking the adoption of process innovation by steel firms to the replacement theory.

Two main conclusions can be drawn from the replacement theory. First, assuming that a firm does not retrench in terms of production capacity and that existing machinery and equipment eventually wear out, the decision regarding replacement is not whether to replace the equipment but, rather, when to do it. Second, since the investment in the existing equipment is a sunk cost, a firm should replace its equipment when the per unit marginal cost of the old equipment equals the per unit average cost of the new equipment, assuming an absence of technological change [Fama and Miller, 1972; Nickell, 1978; Salter, 1960; Terborgh, 1949]. However, this proposition does not hold under continuous technological change. The main reason is that as new equipment is installed and technology progresses, the new equipment begins to

accumulate "operating inferiority" relative to newer technologies which will emerge in the future. As Terborgh [1949] argued:

> It is true that the challenger has eliminated all present available rivals. But it has not eliminated future rivals. The latter, though at present mere potentialities, are important in the contest. For the current challenger can make good its claim to succeed the defender only when there are not future challengers worth waiting for. It must engage, as it were, in a two-front war, attacking on one side the aged machine it hopes to dislodge and on the other side an array of rivals still unborn who also hope to dislodge the same aged machine, but later. (p.55)

This assertion clearly illustrates the dilemma a firm faces in replacing its technologically inferior equipment. If the firm waits for more advanced equipment by delaying its replacement, it will have to bear higher marginal costs over the delay period. But if the firm replaces its obsolete equipment, it gives up the opportunity to adopt more advanced equipment later on, which would yield more cost savings. This dilemma is shown graphically in Figure 1. $MC(t)_{old}$ denotes the marginal cost of the existing equipment as a function of time t and $AC(New)_t$ denotes the average cost of the new equipment installed at various points in time. To simplify the problem, we assume that (i) no switching costs are involved, (ii) the average cost of new equipment available at various points in time is expected to decline over a finite period as a result of technological advances, and (iii) the marginal cost of the existing equipment increases over time because of age.

<u>Insert Figure 1 about here</u>

Without considering technological progress, the firm will replace its existing equipment at T' when its marginal cost equals the average cost of the new,

BT'. We assume that the new equipment will last till T''' and then be replaced with equipment whose average cost is T'''H. The total cost of production from beginning till time T''' is OABFT'''[1], i.e. the sum of the total cost of using the old equipment, OABT', and the cost of using the new equipment, BT'T'''F. But under continuous technological obsolescence, the firm may benefit from delaying replacement of its equipment.

If the firm delays its replacement till T'', its average cost of using the new equipment will be T''E. Let this piece of equipment last till time T.[2] In this case, the total cost associated with its use up to time T is OACT'' plus ET''TJ. The difference in costs between the two alternatives [3] is (BCD - DEGF + GKIJ). If BCD + GHIJ is less than DEGF, the firm is better off waiting till T'' to replace its equipment. In this case, the high marginal costs incurred during the period from T' to T'' and the loss of the benefit GKJI are more than offset by the lower average cost of new equipment available at T''. Thus, it is important that a decision maker weigh the advantages and disadvantages of replacement at any point in time.

Given the benefits and costs of waiting, the problem facing the firm is how to choose the optimal time to replace its equipment. The mathematical model derived below will obtain the optimal timing of replacement under continuous technological change. Although the model is not intended to be descriptive of a real-life situation, we believe that the results derived are of general importance and very relevant to capital investment decisions. We first make the following assumptions to construct the model:

1. The firm maximizes the present value of its investment.
2. The market is relatively competitive and thus the firm is a price taker.
3. Uncertainty is absent.

4. There are no taxes of any kind.

5. The marginal cost of equipment increases with the age of the equipment.

6. The cost of capital is constant over time.

7. New equipment reduces production costs but does not add to the quality of the product and does not change the value of the firm's output.

8. The firm replaces its equipment only once in the planning horizon.

9. Technology progresses over time and thus the production cost declines over time.

10. The replacement takes place instantaneously.

Since the firm is a price taker and new equipment does not change the value of its output, the replacement decision will not affect the firm's revenues. Thus, the objective of the replacement is cost minimization. If the replacement takes place at an arbitrary time T', the cash outflow from time zero to T is:

Cashflow = [Marginal cost of using the existing equipment till T'] + (The net investment in the new equipment + Marginal cost of operating the new equipment - Residual value of the equipment at time T)

in which the net investment in the new equipment is the sum of the fixed cost of the equipment plus the necessary switching costs, minus the salvage value of the old equipment. We let

- r be the cost of capital which remains constant.
- T be the planning horizon of the replacement decision.
- T' be the timing of replacement.
- I(t) be the fixed cost of the new equipment plus the necessary switching costs minus the salvage value of the old equipment at time t.
- MC(t) be the marginal cost of the old equipment.

- o $MC'(T',s)$ be the marginal cost of the new equipment of age s, which is installed at time T'.
- o $RV(T')$ be the residual value at T of the equipment installed at T'.

The cash outflow associated with the use of the existing equipment till time T' and then replacing the equipment is

$$C = \int_0^{T'} MC(t)e^{-rt}\,dt + e^{-rT'}\left(I(T') + \int_0^{T-T'} MC'(T',s)e^{-rs}ds\right) - RV(T')e^{-rT} \quad (1)$$

If we differentiate equation 1 with respect to T' and set the result equal to zero, we obtain the minimum cost as follows:

$$MC(T') + \left[\frac{dI(T')}{dT'} + \int_0^{T-T'} \frac{d}{dT'} MC'(T',s)e^{-rs}\,ds - \frac{dRV(T')}{dT'}\,e^{-r(T-T')}\right]$$

$$-rI(T') - MC'(T',0) - \int_0^{T-T'} \frac{d}{ds} MC'(T',s)e^{-rs}\,ds = 0 \quad (2)$$

Or

$$MC(T') + \left[\frac{dI(T')}{dT'} + \int_0^{T-T'} \frac{d}{dT'} MC'(T',s)e^{-rs}\,ds - \frac{dRV(T')}{dT'}\,e^{-r(T-T')}\right]$$

$$-rI(T') - MC'(T',0) - \int_0^{T-T'} \frac{d}{ds} MC'(T',s)e^{-rs} = 0 \quad (3)$$

This is the necessary condition for the firm to minimize its discounted cash outflows. Further break down of investment into fixed costs of the new equipment and switching costs yields the economic interpretation of equation 3

$$MC_{old} - \text{Net Gains from waiting} = AC_{new} + \text{Switching costs} \;\ldots\ldots(4)$$

A full mathematical derivation of equation (2) and an economic explanation are presented in Appendix I.

Equation (4) indicates that the firm should replace its existing equipment when the marginal cost of the old equipment minus the net economic gains from

delaying replacement of the equipment equals the average cost of the new equipment plus the switching costs. This proposition has seven important strategic implications.

STRATEGIC IMPLICATIONS OF CRITICAL FIXITIES

A. Specialization, Marginal Costs and Switching Costs

Equation (4) demonstrates that, other things being equal, the lower the marginal cost and the higher the switching costs, the less likelihood there is that the firm will replace its existing equipment with new equipment. These effects can be viewed as the fixities of a firm to adopt a process innovation. As suggested by Zannetos, *et al* [1982], high switching costs and low marginal costs result from critical fixities characterizing the firm. As we stated earlier, the term "critical fixities" means an inertia that keeps an organization from innovating and also from responding, and adopting known innovative strategies which are critical to the progress of the firm and, ultimately, to its survival. This inertia is related to three major factor inputs: capital, labor, and management. Thus, critical fixities consist of a capital fixity, a labor fixity, and a managerial fixity; and each represents the inflexibility of a factor input in adapting to innovation, and in general to considering and initiating change.

Capital fixities reflect the amount of inertia associated with physical capital which is manifested in the marginal cost of using the existing equipment and the switching costs associated with equipment change. Low marginal costs normally result from efficient capital intensive operations and a high degree of vertical integration. As capital successfully substitutes for labor and vertical integration substitutes for materials purchased, sunk

costs increase and marginal costs decrease. As a result, it becomes less attractive to adopt advanced equipment. Likewise, as the capital stock and the specialization of capital increases through investment in either cost saving equipment or in vertical integration, switching costs associated with capital are likely to increase. Both low marginal costs and high switching costs restrain change. In other words, the investment in capital goods reflects the commitment of the firm to a certain technology. By making the commitment, the firm becomes locked into that technology and the investment becomes a barrier to exit from that technology. Following this, previous investments may become an exit barrier from an industry, a notion advanced by Zannetos [1966], Caves and Porter [1976], and Harrigan [1980, 1981, 1982].

Labor fixities refer to the inertia on the part of production workers that impinges on management's abililty to adequately respond to change. This restraining may be due to organizational or power issues, often related to unions, or simply to the inability of workers to change or to adapt to an innovation.

Labor unions play an interesting role in labor fixities because they simultaneously increase the marginal cost of the existing labor force through higher wages while increasing the average switching costs of retraining through political opposition. High wages encourage management to consider the adoption of capital intensive innovations, while high retraining costs serve as an impediment. It is difficult to say which effect is likely to predominate, although evidence suggests that the negative effects predominate in the long run. Capital investments "beyond the optimum", because of the monopoly power of unions, create capital fixities which as we have pointed out will come to haunt the firm later on. Further on, there is evidence that, other things being equal, the greater the specialization and the longer people

are employed "doing the same things" the greater will be the switching costs and also the greater the probability that the implementation of innovation will be unsuccessful.

Finally, in some cases, unions transform high labor costs into fixed costs by setting strict work rules, reducing marginal cost and prohibiting outright innovation adoptions.[4]

There is another dimension of the operational activities of a firm which contributes to the increase of labor fixities. Firms seek to reduce costs through specialization of labor. This specialization, coupled with volume production, allows workers to move down the experience curve with the effect of reducing unit costs over time. Thus, the total marginal costs decline, making the existing technology more and more attractive. However, as we have already pointed out, the greater the specialization, the greater the switching cost (retraining workers) for a new technology will be.

Managerial fixities reflect the inability or unwillingness of management to innovate or adopt innovations when it is economically feasible to do so. There are many hypotheses as to the causes of what we call "managerial fixities" but the consequences are the same, resistence to change and insecurity because of technological obsolescence.

Over the years many authors attempted to diagnose managerial behavior. The approach of the classicists of administrative theory stressed the notions of "leadership", "unity of command", "span of control", "authority" and "responsibility". [Gulick and Urwich, 1937; Schell, 1924] These efforts were given new directions by Barnard [1938] who analyzed the administrative process and provided the impetus for the behavioral theory of the firm [Simon, 1957; March and Simon, 1958]. The latter postulates among other notions, a non-optimizing (satisfying) behavior for managers, a quasi-resolution of

conflicts through the use of slack (side payments), stability of expectations an uncertainty avoidance, learning as an extrapolation of experience, and a linkage between the level of aspirations and performance.

Several aspects of the above theory were extended and used to describe and explain specific managerial decisions or to test hypotheses regarding managerial behavior and process. Some of the notions employed to explain resistance to change include uncertainty avoidance [Carter 1971], failure to perceive external reality [Hedberg et al 1975], shortcomings in the process of evaluating technological innovations [Gold, 1983], the NIH (Not Invented Here) syndrome [Katz and Allen 1981], political considerations [Katz and Kahn 1980], improper organizational structures [Burns and Stalker 1961, Thompson 1967, Galbraith 1972, Lawrence and Lorch 1967], and self-justification for the previous course of action [Staw 1981].

Professional technological obsolescence also prevents managers from responding to innovations. Several explanations were proposed for technological obsolescence, for example, organizational and individual factors such as the level of education [Kaufman 1975, Rothman and Porinci 1971], overspecialization [Mali 1969], lack of manpower planning and development within organizations [Burack and Pati 1970, Thompson, Dalton, and Kopelman 1974], lack of reward systems encouraging people to keep abreast of technological developments [Cooper and Jones 1980, Farris 1973], jobs which do not challenge or fully utilize one's skills [Mali 1969, Miller 1972, Kaufman 1974, 1975], and lack of interaction with colleagues [Margulies and Raia 1967]. As managers become obsolete, it is difficult for them to understand, perceive the significance of and accept technological innovations. What is not understood is definitely a threat and will be fought rather than espoused. And no one will fight harder for the status quo or better

articulate the reasons for the inadvisability of the adoption of innovation, than the person who initiated the latest round of technological change. For it is he/she whose knowledge, professional leadership and status will be challenged. According to our observation, the longer a manager stays in the same job, the higher the specialization, the higher the personal switching costs and the lower the personal marginal cost to further professional specialization along the same lines and thus, the more difficult it is to change.

In sum, capital fixities cause low marginal costs of production using the same facilities and technology, and also high capital switching costs; labor and managerial fixities through specialization lower the marginal cost of keeping on the same path and also increase switching costs. The combination of these low marginal costs and high switching costs prohibit adoption of a process innovation for replacement, unless the benefits are so overwhelming as to counterbalance the costs.

Equation (4) demonstrates the economic consequences of the three fixities; it can also help us examine how critical they are in decisions made by the firm.

B. Accounting Costs, Cash Flows and Exit

Considering Equation (4) more carefully, one can clearly see as to why firms often continue to use obsolete equipment and technologies and sustain accounting losses rather than replace their out-of-date equipment. If other firms gradually adopt the latest process innovation, the price is likely to be the average cost of the new equipment including the minimum return on capital. Substituting price for AC_{new} into Equation (4) gives

$$MC_{old} - \text{Price} = \text{Gains from waiting} + \text{Switching costs} > 0 \quad (5)$$

Since the cost of switching to a new technology and, thus, the right-hand side of the equation is most likely to be positive, the implication is that even if the marginal cost exceeds the price, the firm should still not replace its equipment. Both elements of the left-hand side of the Equation (5) are cash-flow items, the marginal cost is a cash outflow and the price is a cash inflow, therefore, when the marginal cost exceeds the price, there is not only an accounting loss but also a negative cashflow.[5] So facing continuous technological change, a rational firm should temporarily suffer an accounting loss or even a negative cashflow and still keep its outmoded equipment. If the firm's cash reserve cannot be sustained long enough to wait for the adverse effects of critical fixities to subside, the firm will go bankrupt. Therefore, these fixities are critical to a firm's survival. In fact, as we will show later, critical fixities have caused the decline of at least one entire industry.

The fact that a firm should suffer accounting losses and still keep its out-moded equipment provides an economic rationale for the "deindustrialization" of America.[6] Probably due to critical fixities, U.S. firms are not willing to, nor should they switch to, modern equipment, despite their losses. Therefore, some industries become de-industrialized. It is hard to argue that firms in these industries are short-sighted. As suggested before, the decision regarding obsolete technologies is not whether to replace but when to replace. The firms facing such decisions may have a long-term perspective and are waiting for more advanced technologies. Simply rushing to buy the most up-to-date equipment, according to our model, may precisely reflect a short-term view which does not provide the firm with a sustainable cost advantage.

C. Technological Innovation as a Strategy for Entry

The critical fixities model also provides an explanation of the entry and exit of firms from an industry resulting from technological innovations. While existing firms are reluctant to adopt new technologies because of critical fixities, other firms may enter the market and adopt the new technology, resulting in a lower cost, and thus, an extra profit. Entrants with new technologies may force existing firms with high critical fixities to exit from the industry.

This seems to suggest a strategy for entry by means of new technology. As critical fixities of incumbent firms prevent them from switching to a new technology, modern entrants can easily outperform existing firms because of lower cost and often a higher value of the end product. This strategy seems to be adopted widely. For example, Amdahl entered the IBM-compatible mainframe computer industry with ECL (Emitter-Coupled-Logic). It was not until ten years later that IBM adopted the ECL for its Sierra Series. Japanese firms are the most notable examples of successfully employing this strategy. The Japanese entered the U.S. auto industry with robotic technology, the semiconductor industry with CMOS[7] (Complementary Metal-Oxide Semiconductor), and the steel industry with gigantic blast furnaces and the Basic Oxygen Furnace. However, this strategy should be used cautiously because critical fixities also imply leap-frog type competition, which may make the victors the victims of the next round of innovation.

D. Critical Fixities and Leap-Frog Competition

Leap-frog type competition is thus the fourth implication of this model. We let the history of an industry be divided into N periods and assume that a process innovation occurs at the beginning of each period. We also assume

that the time periods are so divided that the process innovation introduced in period N+1 is not economically attractive due to critical fixities; and as a result the technology of period N is not replaced. However, as the marginal cost of production increases over time, the technology introduced in period N+1 is economically attractive enough to replace the technology of period N-1. Therefore, at period N+1, while the firms which adopted the technology of period N are not willing to change to the technology of period N+1, entries into and exits from the industry may occur and firms which adopted the technology of period N may suffer accounting losses during period N+1.

Going forward to period N+2, those firms with period N technology will be willing to adopt the technology available in period N+2, while the firms with period N+1 technology will not be willing to do so because of their critical fixities. Consequently, in period N+2, the firms which suffer losses in period N+1 become winners and the winners in period N+1 become losers. Leap-frog type competition is thus manifested: some firms enjoy a short period of gain and, subsequently, a short period of loss. As we will show later, this may explain the rise of the U.S. steel industry in the 50s and then its fall in the subsequent decades.

The leap-frog type competition described above indicates that competitive cost advantages will not be sustainable if the advantages are achieved through investing in modern machinery and equipment given the same product characteristics. Although investing in modern process technologies leads to a lower cost now, the investing firms will incur critical fixities and then be surpassed by firms using future technologies. It seems that, according to this model, modernizing equipment to improve a firm's competitive position may not be an appropriate solution to some declining U.S. industries, and costs serious doubts on the long-term viability of a so-called "low cost strategy"

for these industries. As Zannetos [1983; 1984] pointed out, a lasting solution is more likely to be found in increases in productivity through product innovation rather than pure cost-reducing process innovation of a homogeneous product.

Leap-frog type competition also presents pitfalls for those firms which enter an industry on the coat tails of a new technology strategy in that other firms may easily bypass these new entrants later. Recognizing, however, that critical fixities are necessary evils, entry on the basis of a new technology strategy is still viable if the entrants choose the right time to enter. The right time to enter can be determined by modifying Equation (4). As we have already stressed, the issue involved in an entry of this kind is not simply whether or not to enter the industry, but, more importantly, when to enter. In this case, timing becomes an important strategic dimension.

E. Vertical Integration

The model implies that, other things being equal, a firm should reduce the degree of vertical integraion in an environment of continuous technological change of the manufacturing process. Vertical integraion lowers the marginal cost and thus increases the critical fixities, leaving the firm less able to cope with technological change. A stronger argument may be made against vertical integration in cases where innovations in intermediary goods may affect both the manufacturing process and some of the characteristics of the final product. Unless the firm which produces the final product is the one which creates planned obsolescence of intermediary parts and manufacturing processes, the existence of critical fixities will render it incapable of changing its manufacturing process and introducing new parts which are the result of new technology. Hays and Abernathy [1978], for example, observed that the vertical integration in the U.S. auto industry was the cause of a

delay in the transition from cast-iron brake drums to disc brakes by five years.

F. Mobility Barriers

Porter and Caves [1977] advanced the hypothesis of mobility barriers between strategic groups choosing different technologies. We believe that the existence of critical fixities, as our model suggests, may be the cause of mobility barriers.

As the vintage of technology determines the performance of the firm, technology becomes a critical strategic dimension and could be used to classify firms into different strategic groups. The existence of critical fixities prevents firms of low performance groups from moving to high performance groups which use advanced technologies. Therefore, the notion of critical fixities helps explain the formation of strategic groups within an industry as well a the performance differences between these strategic groups. At the same time our work points out that the existence of mobility barriers, which affects the ability of firms to move from one so-called strategic group to another within the same industry, does not necessarily prevent the entry of new firms into the industry which may effectively compete with the best.

G. The Ambivalence of Technological Change

The rate of technological change plays two critical roles in the replacement decision. On the one hand, it increases the economic gains of delay. As a result, it serves as an incentive for a firm to wait and extend the life of its existing equipment. Continuation of the same manufacturing technology may allow at the same time further specialization of management and labor and increase the switching costs even more. On the other hand,

technological change decreases the average cost of the new equipment and thus accelerates the replacement process. These two roles interact with each other. The time to replace the equipment, therefore, is when the gains from waiting plus the switching costs equal the operating inferiority of the existing equipment.

Finally, this model also provides theoretical underpinnings to the "productivity dilemma" and the "escalating" commitment to the wrong technology. Abernathy [1978] observed that

> as productivity increased, significant technological change became more difficult to change...we see that many years of high rates of productivity have come at a cost—a declining capacity for major innovation." (pp. 3-4)

In other words, as capital substitutes for labor, physical labor productivity increases and thus the per unit marginal cost of the existing equipment decreases. As a result, critical fixities increase, and the firm is less interested in adopting technological innovations for its manufacturing processes. Therefore, a cost of a productivity growth through capital-intensive process innovations is a lower capacity for innovation. And the greater the change at any moment in time the longer it will take for the adoption of another technological breakthrough.

While escalating commitment to previous investments has been interpreted as a psychological phenomenon [Schwenk and Duhaime 1985, Staw 1981],[8] our model argues that, under certain conditions, it is economically legitimate to escalate a firm's commitment to the wrong technology. Once investments are made in an old technology, critical fixities are created. Consider the following scenario: a new technology emerges and is improved, while simultaneously the old technology is also improved. Critical fixities will

induce the firm to invest in the improvement of the old technology rather than switch to the new technology even though the new technology is more efficient than the improved old one. Investments in improving the old technology further increase critical fixities, which then induce the firm to commit even more to the old technology. An illustration of phenomenon is the decision of the United States steel industry to add 48 million tons of Open Hearth (OH) capacity in the 50s, rather than use the Basic Oxygen Furnace (BOF) technology which was superior. Two-thirds of these new capacities were upgraded from the then existing OH shops. Later, in the 60s, steel firms tended to improve the OH shops by adding oxygen lances rather than switch to the BOF (Dilley & McBride, [1967]. This escalating commitment phenomenon may cause the strategic momentum proposed by Miller and Freisen [1980]. It also indicates the importance of choosing the right technology to start with. Once the decision is made, it is difficult to change. In fact the larger "a white elephant" an investment is the greater the economic justification to stick with it if the marginal cost is very low.

In the next section we will use the specifics of the steel industry to further illustrate the strategic implications discussed above. Tang [1985] showed that critical fixities could explain several aspects of the innovation adoption behavior, entry into and exit from, and the performance differences of firms in the steel industry. Taking this work as a starting point, we will at first present an introduction to the steelmaking technologies, so that the impact of technological innovations can be understood and then briefly analyze the dynamics of the U.S. sttel industry in terms of the critical fixities model.

THE STEEL INDUSTRY

Steel can be made either from iron ore or from scrap. Steel mills which make steel from iron ore must go through an integrated process: iron making, steel making, casting, and rolling and finishing. These mills are called integrated mills. Other steel mills make steel from scrap by first refining scrap in the Electric arc Furnace (EF) and then rolling or casting liquid steel into the desired shapes.

Since the 1950s, the steel industry has experienced significant changes in each of the steelmaking stages.

1. Massive cheap iron ore reserves were discovered in Brazil and Australia in the 60s.
2. Gigantic blast furnaces were developed in the 60s.[9]
3. The Basic Oxygen Furnace, a steelmaking furnace, was commercialized in 1954 and soon replaced the Open Hearth as the dominant steelmaking technology.
4. Continuous casting, developed in the late 60s and early 70s, replaced ingot casting as the main casting technology which reduced labor requirements by two-thirds.[10]
5. In the 60s, the capacity of the EF was enlarged significantly. Since then, it has been economical to produce low carbon steel using the EF at an annual capacity of slightly less than one million tons. Mills which use this process are called "minimills", as opposed to large scale integrated mills. Cheap scrap plus the combination of the EF and the continuous casting give the minimills a cost advantage over integrated mills.

The U.S. integrated steel sector, however, was slow in adopting technological innovation and switching to cheap iron ores, thereby losing its domestic and international competitiveness. Our hypothesis is that since the steel industry is a process technology-intensive industry, its decline can be traced to wrong investments made in the 50s, which created critical fixities that prohibited integrated steelmakers from adopting innovations in the subsequent decades.

To evaluate the importance of process innovations to the steel industry, we performed regression analyses on two performance measures against a technology surrogate variable and a variable representing product mix. The two performance measures are profitability measures for the three year averages (1959-1961)[11] of cash flow over gross assets (CFI), and the operating income over net assets (ROI). We define cash flow as operating income plus depreciation, and gross assets as net assets plus accumulated depreciation. The technology surrogate variable is the average annual capacity of blast furnaces.[12] This has been chosen as the variable because historically, integrated steel production has been characterized by significant economies of scale and technological advancements in the steel industry have often been used in upgrading the scale of certain steelmaking equipment [Barnett and Schorsch 1983, Boylan 1975, Gold et al 1984]. The product mix variable, which controls for the effects of potential product mix changes, is steel sheet capacity.[13]

The regression results are given in Table 1, and clearly indicate that process technologies did have an impact on profitability. The coefficients of the BF are significantly different from zero in the two regressions, and the BF scale variable together with a product mix variable can explain over 60 percent of the variation in profitability. These results reveal certain

association between a firm's profitability and process technology. With this in mind, we proceed to use process innovations to explain the structural changes in the steel industry.

Insert Table 1 about here

The U.S. steel industry finished its major expanions in the 50s, during the years when the BOF was in the experimental stage and a decade before cheap iron ores were discovered and continuous casting and gigantic blast furnaces were successfully commercialized. While expanding, U.S. steelmakers used the best technologies available at that time: large blast furnaces capable of producing 1,500 tons of liquid iron per day, large size OHs and ingot casting machines.

In the 1950s, the U.S. steel industry added 47.8 million tons of OH capacity. Also the blast furnace capacity increased from 71.5 million tons in 1950 to 94.7 million tons by 1959.[14] After adding blast furnaces and OHs, steelmakers continued to add ingot casting facilities. Furthermore, as the U.S. iron ore reserves were almost depleted, the U.S. steel industry vertically integrated backward by acquiring iron ore reserves in Canada [Barnett and Schorsch, 1983]. These new facilities helped the industry build its technological superiority in the world and made the U.S. a net steel exporter. At the same time the capital investment in new facilities and the vertical integration resulted in low marginal costs in the years that followed and made adoption of technological innovations in the 60s prohibitive.[15] With the emergence of the BOF, large EFs, and continuous casting in the 60s and 70s, the U.S. integrated steel mills found it difficult to compete with

the minimills and the Japanese steelmaking industry which adopted the new technologies.

Japan decided to develop her steel industry in 1955, just after the BOF was successfully commercialized. Since 1955, Japan has aggressively expanded her steel capacity by adding the most advanced equipment. During the 60s and 70s, the Japanese steel industry experienced the highest growth rate of steel production among major industrial countries. As a result, Japan had at the time the largest and newest steel mills in the world. By 1975, the Japanese blast furnaces included six of the world's ten largest, each capable of piuring 10,000 tons of liquid iron per day. Lacking domestic iron ore, Japan purchased all her requirements from Brazil and Australia. These ores were cheaper and of a higher grade than the U.S. ores. The combination of the new technologies developed in the 60s, and low labor and the iron ore costs positioned the Japanese steelmakers as the low cost steel producers in the world. Consequently, Japanese steel easily penetrated the U.S. market.

As technological innovations in process equipment become universally available, this entry strategy is easy to imitate. History, therefore, repeats itself. South Korean and Taiwan steel companies are now penetrating the Japanese steel markets using the same strategy as used by the Japanese some twenty years earlier, that is to say low labor cost and new technologies. At this time, Japanese steelmakers are asking their government for a quota to be set for foreign steel products, a reaction reminiscent of that of the U.S. firms. Concurrently, Japanese steelmakers also plan to fight back with another generation of casters: plate casters, which save the expensive rolling process. When these casters are available, Korean and Taiwan steelmakers may not be able to adopt them because of the current creation of their own critical fixities.

The U.S. integrated steel makers are well aware of the development of continuous strip and sheet casters. Given a large stock of ingot casting machines, the U.S. steel industry should be able to bypass continuous slab and bloom casters, and adopt strip and sheet casters in the future. However, continuous plate casters will not be available for another five to ten years. Given the great inefficiency of ingot casting, it is unlikely that U.S. steelmakers can wait that long without facing certain liquidation. From a strategic point of view, investing in continuous bloom and slab casters now is only a short-term solution with long-term detrimental effects.

Minimills, with new technologies and consequent lower costs, have also gained a significant share of the market which has been traditionally dominated by integrated steel makers. In 1960, ten or twelve minimills shared about two percent of the market [Miller, 1984]. In 1984, fifty minimills shared twenty percent of the total U.S. steel production capacity.

The integrated steel sector being slow to respond to these changes simply retrenched. In 1960, there were 53 integrated steel mills; by 1983, only 33 were still in operation. The combined accounting losses of the steel industry in the 1982-1984 period exceeded $6 billion. Today, the U.S. integrated steel sector probably has the least efficient steelmaking equipment in industrial countries.[16]

The above analysis illustrates that there are three distinct strategic groups in the U.S. low carbon steel market: the U.S. integrated steel-makers, the Japanese integrated steelmakers, and the minimills. Critical fixities act as a mobility barrier preventing firms to move from one group to another. It also illustrates that given the relatively high capital and labor costs of the U.S. steel industry, pursuing process innovations will be futile because this strategy creates critical fixities and cannot close the gap of

cost differences between the U.S. and Japan. A strategy of product innovations and a matching of process and product life cycles is both more consistent with the strengths in technology of the United States and a more plausible strategy to enhance the U.S. steel industry's international competitiveness.

CONCLUSION

This paper explained the notion of critical fixities and analyzed its theoretical foundations. It then discussed some of the strategic implications of critical fixities such as leap-frog competition, entry with new technology strategy, escalating commitment to the wrong technology, timing of investment as a strategic dimension, lowering vertical integration, and critical fixities as mobility barriers. Critical fixities also explain the productivity dilemma and the rationality of using obsolete technologies in the face of accounting losses and even negative cash flow. Additionally, this paper used critical fixities to explain the decline of the U.S. steel industry and the rise and fall of the Japanese steel industry. Specifically, we have shown how badly-timed investments in equipment created detrimental critical fixities for the U.S. steel industry; and also provided the theoretical foundations which explain the entry into and exit from the steel industry.

We consider this paper as the starting point of challenging research efforts on productivity and innovation. Given that critical fixities are the result of a firm's strategy toward the management of technology and that the U.S. economy will most likely have to rely on technology intensive industries, the underlying causes of managerial and labor fixities must be exhaustively researched and clearly understood. Only then will we be able to find ways,

most likely through education and job rotation, of removing these critical barriers to product and process innovation.

Capital fixities, the third major component of critical fixities, also open up several avenues of research within the setting of those capital intensive industries which experience technological change, such as the automobile industry and the semiconductor industry. These two industries are facing the same strategic issues as the steel industry as they attempt to cope with the challenge of Japanese firms which employ strategies for entry with the aid of new technology. Capital budgeting methodologies as well as processes need to be further researched especially as they pertain to the replenishment and expansion of capacity. Alternative linkages between manufacturing strategies and long-range strategies for products must be explored so that the detrimental aspects of capital fixities will be minimized and productivity will be allowed to continuously increase. One particular strategic implication of this is that a firm could adopt a strategy of product innovation and use it to drive process technology and its life cycle so as to avoid the trap of critical fixities created by adopting previous process innovations. This tentative conclusion requires further qualifications and investigation. We are excited by the robustness of the notion of critical fixities and hope that more theoretical and empirical research, by us and others, will prove that it is a vital concept in formulating competitive strategy.

FOOTNOTES

1. We will (a) assume that residual values are accounted for in the cost curves and (b) ignore discounting of the costs for simplicity. The latter assumption does not affect the main thrust of our arguments. Both assumptions are removed later.

2. We assume that the new equipment has the same ex ante life as the equipment it replaces.

3. The assumption is made that a replacement will take place, under the first alternative, at time T''' with equipment, the average cost of which is T'''H.

4. For example, due to strict work rules, it takes 7 man-hours to produce a ton of steel in unionized Bethlehem Steel's Steelton EF shop. This is three times more than the 1.9 man-hours that it takes non-unionized Chapparal Steel's EF shop.

5. Some times the loss carry back may result in a positive cash flow.

6. Wall Street Journal, February 20, 1986.

7. Business Week, May 23, 1983.

8. This hypothesis was first advanced by Charles Schwenk of the University of Illinois, Urbana-Champaign.

9. From the late 50s to the early 70s, maximum daily output of the blast furnace increased six times, from 1,600 tons to over 10,000 tons.

10. Battelle Memorial Institute [1964].

11. 1960 was the last year when annual capacities of blast furnaces were reported.

12. The main reason for choosing the scale of the blast furnaces as the surrogate technology variable is that steelmaking facilities are normally built in consecutive years, and the vintage of the equipment at a particular stage is representative of the vintage of the steel plant. Furthermore, because facilities are built consecutively, high correlations exist between the vintage of different facilities, which pose milticollinearity problems.

13. Steel strips and sheets are the most expensive low carbon steel products.

14. American Iron and Steel Institute (AISI), Annual Statistical Report, Washington, D.C.: AISI, 1950-1960.

15. Tang (1985) has shown that due to a combination of low marginal costs and high switching costs, the U.S. steel makers were unwilling to switch to cheap overseas iron ores, gigantic blast furnaces, basic oxygen furnace, and continuous casting.

16. U.S. Congress, Office of Technology Assessment, Technology and Steel Industry Competitiveness, Washington, D.C.: U.S. Government Printing Office, 1980.

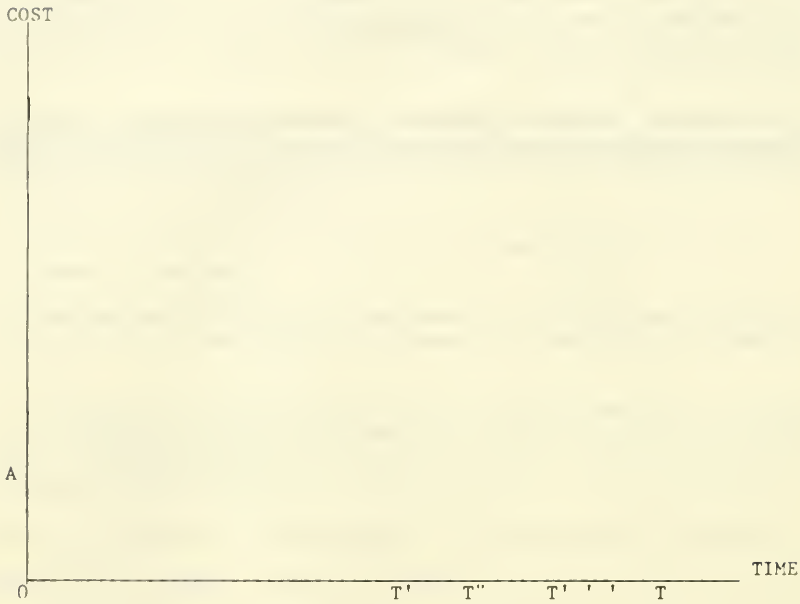

Figure 1 Optimal Timing of Replacement

Table 1

The Effects of Process Technology on a Steel Firm's Profitability

Dependent Variable	Constant	Blast Furnace Log(BF)	Sheet&Strip Capacity SSC	R^2	$\bar{R}^2$	Standard Error
		Coefficients				
Cash Flow / Investment (CFI)	-54.7* (2.38)	4.61* (2.53)	8.40** (4.01)	0.708	0.670	1.86
Op. Income / Investment (ROI)	-69.5* (-2.09)	5.63* (2.15)	10.8** (3.57)	0.651	0.605	2.67

Number of Observations: 18
t-Statistics in parentheses
*Indicates significance beyond the 0.05 level
**Indicates significance beyond the 0.01 level

Definitions of Independent Variables:
Log(BF): Natural logarithm of the average annual capacity of blast furnaces.
SSC: Steel sheet and strip annual capacity as a percentage of total steel products annual capacity.

Source: 1. Moody's Investors Service Inc. Moody's Industrial Manual New York: Moody's Investors Services Inc. 1959-1961.
2. American Iron and Steel Institute (AISI), Directory of Iron and Steel Works of U.S. and Canada, Washington D.C.: AISI 1960.

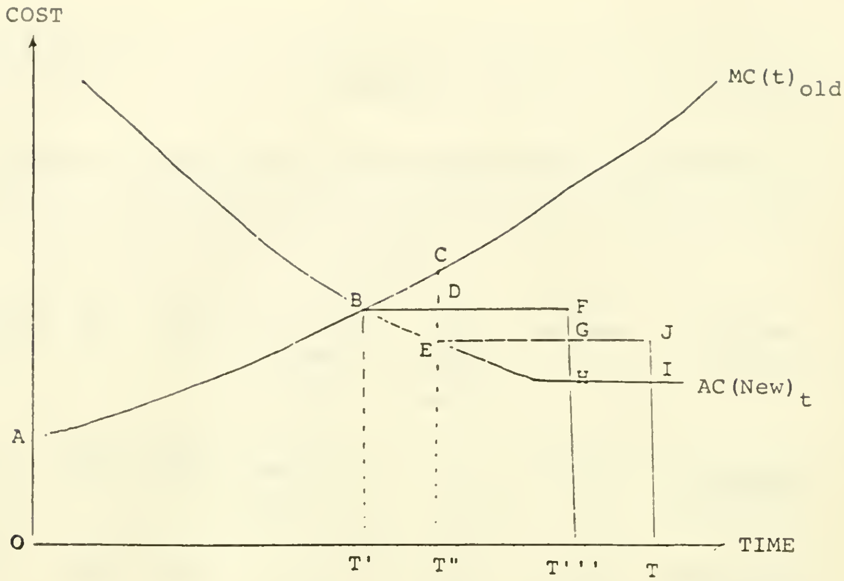

Figure 1 Optimal Timing of Replacement

Appendix I

The cash outflow of operating the existing equipment till time T' and then replacing the equipment is

$$C = \int_0^{T'} MC(t)e^{-rt}\,dt + e^{-rT'}\left(I(T') + \int_0^{T-T'} MC'(T',s)e^{-rs}ds\right)$$

$$- RV(T')e^{-rT} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

To minimize the cash flow, differentiating equation 1 with respect to T' we get

$$\frac{dC}{dT'} = MC(T')e^{-rT'} - re^{-rT'}\left[\left(I(T') + \int_0^{T-T'} MC'(T',s)e^{-rs}\,ds\right)\right]$$

$$+ e^{-rT'} * \frac{dI(T')}{dT'} + e^{-rT'} * \frac{d}{dT'}\int_0^{T-T'} MC'(T',s)e^{-rs}\,ds$$

$$- \frac{dRV(T')}{dT'}\,e^{-rT}$$

Canceling $e^{-rT'}$ gives

$$MC(T') - rI(T') + \frac{dI(T')}{dT'} - \frac{dRV(T')}{dT'}\,e^{-r(T-T')} + \int_0^{T-T'} -rMC'(T',s)e^{-rs}ds$$

$$+ \frac{d}{dT'}\int_0^{T-T'} MC'(T',s)e^{-rs}ds \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (2)$$

The last two terms need further simplification. Using integral by parts we get

$$\int_0^{T-T'} -rMC'(T',s)e^{-rs}\,ds = \int_0^{T-T'} -re^{-rs}\,ds\; MC'(T',s)$$

$$= e^{-rs}MC'(T',s)\Big|_0^{T-T'} - \int_0^{T-T'} \frac{d}{ds} MC'(T',s)e^{-rs}ds$$

$$= e^{-r(T-T')}MC'(T',T-T') - MC'(T',0)$$

$$- \int_0^{T-T'} \frac{d}{ds} MC'(T',s)e^{-rs}ds \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

The last term in equation (2) is

$$\frac{d}{dT'} \int_0^{T-T'} MC'(T',s)e^{-rs}ds$$

$$= \int_0^{T-T'} \frac{d}{dT'} MC'(T',s)e^{-rs}ds - MC'(T',T-T')e^{-r(T-T')} \ldots\ldots (4)$$

Substituting (3) and (4) into (2) gives

$$MC'(T')-rI(T')\,\frac{dI(T')}{dT'} - \frac{dRV(T')}{dT'}\,e^{-r(T-T')} + e^{-r(T-T')}MC'(T',T-T')$$

$$-MC'(T',0) - \int_0^{T-T'} \frac{d}{ds}MC'(T',s)e^{-rs}ds + \int_0^{T-T'} \frac{d}{dT'}MC'(T',s)e^{-rs}ds$$

$$-MC'(T',T-T')e^{-r(T-T')}$$

which is equal to

$$MC(T') + [\frac{dI(T')}{dT'} + \int_0^{T-T'} \frac{d}{dT'} MC'(T',s)e^{-rs}\, ds - \frac{dRV(T')}{dT'} e^{-r(T-T')}]$$

$$-rI(T') - MC'(T',0) - \int_0^{T-T'} \frac{d}{ds} MC'(T',s)e^{-rs} ds \dots\dots\dots\dots (5)$$

Setting Equation (5) to zero represents the first order condition of cash outflow minimization. Solving for T' we get the optimal timing of replacement for the existing equipment. Before proceeding to the implications of this equation, an understanding of the economic interpretations of the terms in Equation (5) must be achieved. Consider $dI(T')/dT'$;

$\int_0^{T-T'} \frac{d}{dT'} MC'(T',s)\, e^{-rs} ds$; and $\frac{dRV(T')}{dT'}\, e^{-r(T-T')}$.

The first expression reflects the effects of the timing of equipment replacement on the investment cost, I, which includes the salvage value of the old equipment, the purchase price of the new equipment, and the switching costs. The second and third expressions reflect the timing effect on the marginal cost and the residual value of the new equipment. Since technology progresses over time, the sum of these three expressions can be viewed as the net effect of technological progress on those costs. If switching costs are constant over time and the salvage value is minimal then the sum of these three expressions should be negative because (i) the residual value of the equipment at T

increases with T' and thus $(\frac{dRV(T')}{dT'} e^{-r(T-T')})$ is negative and (ii) as technology progresses, the average cost of new equipment, including fixed costs and marginal costs, is reduced. These costs reductions, represented by the absolute value of the sum of these two expressions, are the economic gains in costs obtained by waiting for a more advanced technology.

Next we consider the expression $[MC'(T',0) + \int_0^{T-T'} \frac{d}{ds} MC'(T',s) e^{-rs} ds]$. $MC'(T',0)$ is the marginal cost of the equipment installed at T' when it is new. The expression $\int_0^{T-T'} \frac{d}{ds} MC'(T',s) e^{-rs} ds$ represents the averaged, time adjusted increases in the marginal cost of the new equipment. Thus, the sum of these two terms is the time-adjusted marginal cost of the new equipment averaged over the period from T' to T. To this sum we add $rI(T')$, the net investment times cost of capital which gives us the average cost of the new equipment. The economic interpretations of these terms are now apparent.

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